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Lightning Protection and Instrumentation at Kennedy Space Center

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Abstract

Lightning is a natural phenomenon, but can be dangerous. Prevention of lightning is a physical impossibility and total protection requires compromises on costs and effects, therefore prediction and measurements of the effects that might be produced by lightning is a must at locations where people or sensitive systems and equipment are exposed. This is the case of the launching pads for the Space Shuttle at Kennedy Space Center (KSC) of the National Aeronautics and Space Administration. This report summarizes lightning phenomena with a brief explanation of lightning generation and lightning activity as related to KSC. An analysis of the instrumentation used at the launching pads for measurements of lightning effects with alternatives to improve the protection system and up-grade the actual instrumentation system is indicated.

Keywords

Lightning, Lightning Currents, Lightning Prediction, Lightning Instrumentation, Lightning Protection,

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LIGHTNING INSTRUMENTATION AT KSC

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ABSTRACT

This report summarizes lightning phenomena with a brief explanation of lightning generation and lightning activity as related to KSC. An analysis of the instrumentation used at launching Pads 39 A&B for measurements of lightning effects is included with alternatives and recommendations to improve the protection system and up-grade the actual instrumentation system. An architecture for a new data collection system to replace the present one is also included. A novel architecture to obtain lightning current information from several sensors using only one high speed recording channel while monitoring all sensors to replace the actual manual lightning current recorders and a novel device for the protection system are described.

LIGHTNING INSTRUMENTATION AT KSC

Jose L. Colon

1. INTRODUCTION

Lightning is a natural phenomenon, but can be dangerous. Kennedy Space Center is located near the maximum lightning activity and lightning represents a hazard for all phases of space lift operations. Prevention of lightning is a physical impossibility and total protection requires compromises on costs and effects, therefore prediction and measurements of the effects that might be produced by lightning is a must. The Air Force Weather Squadron provides prediction of lightning at KSC using several ground-based instruments and it is well attended. Protecting the launching pads from lightning effects cannot be absolute, but some critical sections are now exposed to possible lightning strikes. Adding more protecting wires can reduce the probability. Adding an inexpensive corona device to the actual protection wires might also help to reduce this probability, but further analysis and investigation is needed on this subject.

Measurements on several electrical parameters are needed to evaluate possible effects on sensitive electronic equipment and most of them have been measured. But the electric and magnetic fields induced by lightning currents in the Payload Changeout Room (magnitudes and rate of change) are not been monitored. This data is needed to determine possible damaging effects into payload. The system in use to determine the lightning effect in the slide wires is a manual reading system, which is time consuming and requires a complex calibration process and does not provide all the needed data. This system can be replaced with a novel one that can provide the needed data in electronic format for integrated processing using only one high-speed channel recorder.

2. LIGHTNING PHENOMENA

The atmosphere is an electrical insulator or not a good conductor. Due to sun energy or radiation, moisture is always present and accumulates forming clouds. Since the atmosphere with the clouds is a gas with particles in continuous movement, due to the same sun activity, there are collisions continuously, and an ionization process is present that produces a huge amount of positive and negative charges. These charged particles tend to separate under the influences of upper drafts and gravity and same type of charges accumulates in large sections of the cloud [1]. This will produce an enormous electric potential (voltage that can amount to millions of volts) within the cloud, between clouds, between clouds and ground, and also between cloud and upper atmosphere or stratosphere.[1]

When an insulator; any insulator (solid, liquid, or gaseous) or a semiconductor, is subject to a high voltage across it, the covalent bonds of the molecules, will "breakdown"(as it is named) producing a large amount of conducting electrons and the material becomes a good conductor. (This effect is known as the Zener breakdown in solid semiconductors and Plasma for gasses.) The total voltage will be distributed between the charged regions and, since it is a gas with moisture in a continuous movement, density is not uniform and the ionization will take place in sections called step leaders. Once a section is ionized will affect the voltage distribution and higher voltages will be present at other sections still not ionized. This sequence is like a domino effect, and will occur real fast. It has been estimated to occur in microseconds[2]. When the steps meet, a conducting channel is available for charges to move or discharge, and lightning begins.

Since the effect will occur between high voltage regions, lightning can occur within the cloud, between clouds, between clouds and ground, and between clouds and upper atmosphere.

Since the process is produced by a high intensity electric field, the field can be measured and it is used to predict lightning occurrence.

Once the path is available, which happens to be a good conducting path between two charged regions with millions of volts, it will produce a sudden current flow up to hundreds thousands amps. Peak power has been estimated in gigawatts. The current flow will start fast with rise time measured in the range of 2 to 10 microseconds. The length and duration of each lightning stroke vary, but typically average about 30 microseconds [3].

This high current, changing at such a fast rate, will produce magnetic fields in the area that will induce voltages and currents on other nearby conductors due to magnetic coupling. The induced voltages or currents can affect and damage sensitive electronic equipment. Another effect, that produces high voltages nearby, is also present in a lightning strike. Due to the high and fast changing electrical field, any nearby exposed conductive (or semi-conductive) and electrically insulated section will be charged by capacitive coupling that can also produce ionization and an electrical path between that section and grounded areas generating sparks between them. This effect can also damage sensitive equipment and will be very dangerous if combustible materials are present. Notwithstanding, this capacitive coupling effect can be eliminated with good grounding techniques.

The magnetic field produced by the lightning current can be measured and it is used to detect that lightning has occurred and how strong was it.

Since lightning is a high voltage discharge, the generation of high energy particles like X rays and Gamma rays had been predicted. A recently research at the University of Central Florida by Dr. Joseph Dwyer obtained data indicating that X rays are present in lightning strikes.

Since the lightning flash occur in microseconds, the lightning channel will be heated to the order of 20,000 degrees C or more (3 times the temperature of the surface of the sun!), and the air expansion will produce a shock wave (for approximately the first 10 meters), then decay to a sonic wave or thunder as it propagates away from the channel.[1]

This sonic wave can be measured and is to be used to accurate locate the strike point. [4]

The cloud to ground lightning strikes is not the most common type, but it is the most damaging, and dangerous form of lightning. The event can start with a corona effect from sharp pointed conductive objects at ground level. (This is a basic concept for lightning rods)

The lightning flash is composed of a series of strokes with an average of about three to four per strike. The initial stroke usually produces the strongest current and successive strokes will be less than half the previous stroke current. Fifty percent of all strikes will have a first strike of at least 18KAmps, ten percent will exceed 65KAmps level and only one percent will have over 200KAmps. The largest strike ever recorder was almost 400KAmps. [3]

3. LIGHTNING PREVENTION

Since Benjamin Franklin, the use of lightning rods in preventing or reducing the damage from direct lightning strikes has been demonstrated. But, many attempts have been done to market other types of lightning protection systems claiming prevention properties. The Charge Transfer Systems and the Early Streamer Emission are two examples. Other researchers have analyzed this subject and their conclusion is that these systems do not work. [5a, 5b] One of those systems

was tested at KSC and results confirmed that conclusion.

4. LIGHTNING PREDICTION

Lightning and weather has a direct relationship; weather data is used to predict lightning and lightning data is used for weather prediction. Investigations using rockets, high-altitude airplanes and spacecrafts had been carried out and there are other lightning related research projects in progress focusing on the relationships between global and regional lightning activity and rainfall, linking electrical development to the environments of surrounding storms.

Researchers to determine the relationship between the quasi-static ground electric field and the occurrence of lightning have done studies, but none are conclusive. Further research is needed. Several experimental spacecraft systems are available with weather data that also provide lightning data: the Lightning Image Sensor on Tropical Rainfall Measuring Mission with circular orbit that can locate and detect lightning with storm scale resolution, the Optical Transient Detector, that detects momentary changes in an optical scene which indicates occurrence of lightning and the Lightning Mapper Sensor in a geostationary orbit that detects all forms of lightning, determine flash rates, storm motion and evolution.[6]

There are also Ground Based Lightning Detection Networks with magnetic direction finders that cover the entire USA and determine direction toward a detected electromagnetic discharge [1]

5. LIGHTNING HAZARD AT KSC

Lightning presents a significant hazard to all phases of space lift operations. These activities, which often occur outdoors, can involve propellants, ordnance, and sensitive electronic systems, all at risk from nearby or direct lightning strikes. During the actual launch, the vehicle and its payload are even more at risk because of the threat of a triggered strike. [7]

KSC is located near the center of maximum lightning activity. The avoidance of lightning strikes to a spacecraft during launch relies heavily on the ability of meteorologists to accurately forecast and interpret lightning hazards to NASA vehicles under varying weather situations. [1]

Severe hazards for NASA due to lightning have been well documented. One major incident occurred during the 1969 launch of the Apollo 12 mission when lightning briefly knocked out vital spacecraft electronics. Fortunately, the astronauts regained control.

The unmanned Atlas Centaur 67, which carried a Naval communication satellite, was determined to have been struck by a triggered cloud-to-ground lightning flash on March 26, 1987. The lightning current apparently altered memory in the digital flight control computer. This glitch resulted in the generation of a hard-over yaw command, which caused an excessive angle of attack, large dynamic loads, and ultimately the breakup of the vehicle. [1]

On a smaller scale, two sounding rockets being prepared for launch from NASA's Wallops Island in 1987 were prematurely launched as a direct result of lightning. [1]

6. KSC LIGHTNING FORECAST

To assess the triggered lightning threat, the United States Air Force and NASA jointly developed a complex set of weather launch commit criteria (LCC) [8]. Air Force 45th Weather Squadron evaluates these LCCs (and detects and forecasts natural lightning), using an extensive suite of instrumentation deployed throughout the ER and KSC. Five independent ground based systems

are in used for this purpose with closer spaced detectors to provide real time location of lightning in a 6 to 10 Kilometers range with 5% resolution. [9,10]

7. LIGHTNING PROTECTION

Traditional lightning protection has proven to be the best solution. The principle is simple: provide a Faraday cage type of structure or equivalent by placing preferential strike points using electrical conductors higher than the object to be protected and connected to a good grounding system to carry the damaging currents. It is also needed to provide appropriate transient protection on power and signal wires entering the structure. [3] Lightning rods, or sharp pointed electrical conductors at the highest points in an area, connected to a good ground plane has proven to provide protection from lightning strikes.

8. KSC LIGHTNING PROTECTION AT LAUNCH PADS

The launching pad is a massive conductive structure with a good grounding system. It also has appropriate transient protection on power and signal wires. But, the Space Shuttle, when in place before launch, is exposed to lightning. A catenary steel wire is installed on top of the structure on an electrical insulator (fiber glass mast, 70 feet tall on top of the metal structure), extending 1,100 feet north and 1,100 feet south, well grounded at both ends, to provide a preferential strike point for lightning. (Good grounding is a critical condition for this purpose and it is required to be tested periodically.)

There are also seven slide wires to provide an escape route for personnel. Another catenary wire is installed on top of the slide wires to reduce the probability of a strike to the slide wires.

9. LIGHTNING MEASUREMENTS AT KSC LAUNCH PADS A&B

Lightning strikes produce a high magnetic field with a fast rate of change that will induce high voltages on conductors in the nearby surrounding area. Electric resonant effects of the protecting wires and the structure can also contribute to high-induced voltages. Since the payload is typically sensitive electronic equipment that can be damaged by transient induced overvoltages; existing launch procedures require that, in the event of nearby or direct lightning strike, launch procedures be suspended and system level tests be performed to confirm that damage or upset has not occurred.

The catenary wire on top of the structure provides a means to measure the magnitude and duration of the strike current. A recorder is always monitoring the current at both ends of the wire. (CWLIS equipment)

The Vent Line is a critical system that requires electric signals for operation and the current waveform on this line is also monitored with the same CWLIS recorder.

AC power lines (AC and Neutral), DC Power Supply lines (Positive and Negative), and a system ground line are monitored continuously to detect transient overvoltages and both T/O cables are monitored for induced currents. (LIVIS equipment).

Each slide wire and the catenary wire on top of them are monitored with current recording devices (LCR equipment). This is a very simple, passive, and low cost device that can record the peak value of the lightning current. Each catenary wire current is also monitored with this type of current recorder as a back-up provision.

The Operational Television System (OTV) is a video recording system to provide video images for location of the strike. Three images need to be visually analyzed to locate the strike point. Another instrument; the Sonic Lightning Location system, is to be installed at the launching pads. This equipment determines the time of sound arrival and, by triangulation techniques, can locate the strike point. This equipment promises to measure electronically the location of the lightning strike with an accuracy of better than 5 meters in a 500 meters radius. [11]

10. KSC LIGHTNING PROTECTION SYSTEM LIMITATIONS

The Catenary Wire, used to provide lightning protection, is a long steel wire electrically isolated from the structure (approx. total length of 2,500 feet) that should have an equivalent inductance in the order of several hundreds microHenries. [12] The wire needs to be grounded at both sides forming a conductive loop with the ground plane. This loop will be charged with current from the lightning strike. This arrangement can produce higher induced voltages than without it, but the wire is needed as a protective means from a direct strike! (Its natural response will be part of the effects. See Appendix B for oscillatory response of the wire.)

The catenary wire will receive most of the strikes, but cannot provide total protection to all the slide wires nor the Vent Arm, the External Tank, nor Orbiter. These critical sections are under the so called "cone-of-protection" or "zone of protection" concept, but this concept is used to explain lightning protection on ordinary structures that are not too tall. The "Rolling Sphere" concept, incorporated into lightning codes, is a better concept and it has become the standard practice for design. Applying this concept to the Pads, the catenary wires are not protecting these critical sections. (The Orbiter will be protected when the Rotary Service Structure is in the mate position.) Data available (without the Orbiter) indicates lightning strikes at the pad but not on the catenary wires.

The slide wires are not all protected by the catenary wires. Lightning can strike the outer ones and it has already happened. If lightning strikes a slide wire, it can produce metal spots and/or may weaken the wire affecting its performance as a fast escape mechanism, therefore it is required to be tested after a direct strike onto it.

11. INSTRUMENTATION SYSTEM LIMITATIONS

A. Lightning Current Recorders (LCR)

Testing each slide wire is a time consuming process and often unnecessary. If data of the lightning event is available indicating which wire was stricken and if the strike was strong enough to cause any damage to the wire, it will avoid unnecessary testing and delays.

Although the testing process of the slide wire has been greatly improved with robot TV cameras, the data provided by the LCRs for each slide wire indicates peak current only, and does not indicate time duration of the current or waveform, which is an important factor to determine potential damages.

Furthermore, the maintenance and reading of the LCRs, is a manual process, the device requires a complex calibration procedure, and spare parts needed are no longer commercially available.

B. Lightning strike location

The resolution of magnetic field lightning detection system used to predict lightning occurrence is not enough to determine location of the strike. (Resolution of that system is in the order of 350 meters.) Data from the television camera system not always provide an accurate location of

strike. It has happened that only one or two cameras have provided needed pictures of the strike. The new Sonic Lightning Location system can overcome this limitation.

C. Electromagnetic field

Power lines (AC and DC), and control lines are monitored in the Mobile Launch Platform, but the electromagnetic field inside the Payload Changeout Room (PCR) is not been measured. The electromagnetic field intensity can indicate the possibility of damage to sensitive components. The rubber seals around the mating surface of the PCR fitting against the orbiter or Payload Canister are electrically open spaces where the magnetic field can penetrate. The study, "Induced Lightning Effects inside Payload Changeout Room" [12], demonstrates the presence of magnetic induced fields inside the room due to lightning currents on the catenary wires.

D. Vent Line Pic Cable current sensor

Vent Line Pic Cable is been monitored for induced current, but waveforms show too high noise present in the signal and signal seems to be an induced voltage from the magnetic field, not real current in the cable.

12. CAPE CANAVERAL AIR FORCE STATION

At Cape Canaveral Air Force Station launching pads (SLC-17B: Delta, SLC-36B: Atlas, SLC-40: Titan) a Faraday Cage type of structure is used with 28 wires electrically interconnected providing a good protection system.

A measuring instrumentation system called On-Line Monitoring System (OLMS) with 16 high speed data channels that can measure and record the magnetic field, electric field, transient voltages and induced currents is in used. (The catenary wires current are not all measured, only two of them, because it will require too many channels for that purpose) The OLMS system was developed by SRI International to support spacecraft launches at a number of launch sites in the United States. OLMS is installed on SLC-17B (Delta), SLC-36B (Atlas), and SLC-40 (Titan) at Cape Canaveral, and SLC-3E (Atlas) and SLC-4E (Titan) at Vandenberg Air Force Base. [13]

13. ALTERNATIVES AND RECOMMENDATIONS

A) Protection

Protection from lightning strikes is a safety issue. Although absolute protection is not possible, any reasonable measure that can reduce the probability of a lightning strike to critical areas shall be seriously considered.

_Adding more catenary wires, closer to the vehicle (in the horizontal projection, further in the vertical projection) and electrically interconnected will reduced that probability providing a better protection system and will reduce the electrical parameters of the array also reducing induced voltages. (The optimum location and the strength of the actual supporting mast for the additional load will need evaluation.)

_Reinstall the original wire used for lightning protection at the center of the lightning mast and electrically interconnect to the main catenary wires, this will reduce the electrical characteristics of the array. A sensor connected to one recorder channel will be needed for this wire

_Adding lightning rods on top and upper sections of the catenary wires to stimulate possible

corona effect for a better preferential strike area, instead of nearby sections, shall provide better protection. The idea can be accomplished with sharp pointed lightning capturing rods arranged in a star or crown shape form for better effect and easy installation. This inexpensive corona device (CD) should be mechanically and electrically connected to the catenary wires. This is a novel device based on the same old principle of the lightning rods that can make the catenary wires more attractive for lightning strikes than its surrounding structures. Several CDs spaced apart at the top and upper section of the catenary wires should provide a better preferential area for lightning strokes. This idea is based on data from two studies to protect photovoltaic (PV) panels [14,15], and will require investigation and analysis. Furthermore, the weight that can be added to the catenary wire needs to be analyzed to decide material to be used in the construction of the CDs and how many can be safely added. A robot mechanism, similar to the one used for testing the slide wires, can be developed to simplify the installation of the CDs without taking the wires down. These CDs, properly designed, will also dampen or reduce the mechanical vibrations of the wire, thus reducing the mechanical stress. A sample drawing for these CDs is included in Appendix C of this report.

Evaluate cost of installing one or two more wires on top or slide wires to protect them from direct strokes versus cost of testing and possible replacement of the wires due to lightning effects. (If the actual wire on top of the slide wires is relocated, only one additional wire will then be needed for this purpose.)

Eliminate the insulated section of the wire on top of the slide wires and electrically interconnect with the main catenary wire. This wire does not have to be insulated from the main catenary wire if current is measured on each wire, including this wire. The interconnection will contribute to reduce the electrical parameters of the array. (The insulation in used will not really “insulate” because, if a stroke hits that wire, the inherent inductance of the wire will maintain the current flowing, shorting it to the main catenary wire if the lightning path tends to open.)

B) Measurements

a) Modify or Replace Lightning Current Recorder System

-Modifications: Five possible set-ups for this system

1. Install current transformers connected (wired) to the recorder used for catenary wires with a multiplexer
2. Same as one above, but with new multiple channel measuring and recording system (one channel for each slide wire)
3. Develop a new detector circuit with local AC Powered and using same AC power lines for communication
4. Develop a new detector circuit with battery power and storage of data for wireless retrieval.
5. Develop a new detector circuit with battery power and wireless communication.

-Replacement

Develop a new system with one current sensor for each slide wire, interconnected to one recording channel and a monitoring circuit with slave current sensors for each sensor line. This is a novel architecture that will require only one high-speed recording channel while providing needed data for each wire. The monitoring circuit will detect and store the peak level and time of arrival. The arrangement can also be used to monitor several catenary wires, but the “latch”

circuit should select the first signal (above a defined threshold level) for waveform storage. A block diagram or architecture for this recorder system is included in Appendix A.

b) Accurate Lightning Locator System

The new SOLLO System should be finally installed and tested.

c) Electromagnetic Field Recorders

Install Electromagnetic Field Recorders or sensors at Payload Changeout Room
Or provide portable temporary magnetic field recorders that can be placed near sensitive equipment. (If at least three sensors are installed at the PCR, this portable recorder will not be needed.)

d) Power and Communication Lines

If power and communication lines are to be connected to payload equipment, provide temporary transient voltage recorders or sensors for each line.

d) Vent Line current sensor

Add a current sensor placed parallel to the Vent Line current sensor but without the inner cable, and measure the differential signal between them to cancel the magnetic field induction signal.

e) Previous recommendations for PCR

Implement the recommendations indicated in report: "Lightning Effects in the Payload Changeout Room"[12]. All these recommendations will contribute to reduce hazards and to reduce induced magnetic fields inside Payload Changeout Room.

C. System Integration

The recommended systems above provide the collected data from sensors in a format that can be analyzed and displayed with proper algorithms (except for the TV images, if used). This will allow generation of the needed information: magnitude, rate of change, and time duration of the electromagnetic fields, voltage, and current signals and location of lightning strikes in an integrated format for easy access and displaying even on the Web. The actual LIVIS system can be up-graded adding another four channels recorder for the new electric and magnetic sensors but it will require a program to integrate the data for proper display.

The OLMS system does include the integration program. Both systems will need the new current recorders and the SOLLO system. Block diagrams for both systems are included in Appendix A.

14. CONCLUSIONS

The Lightning Protection System and the Lightning Instrumentation System installed at KSC Launching Pads 39A&B can be up-graded to provide a safer system that will reduce risks, re-testing and delays. Two more catenary wires on the vehicle side of the Pads with the corona devices installed, reinstallation of the original center wire, and another wire and relocation of the actual catenary over the slide wires, will provide a better protection system. The actual instrumentation system can be up-graded by adding another four channels recorder with electric

and magnetic sensors and the needed program, or installing the OLMS system. Both systems will need the new current recording system and SOLLO system to obtain an integrated lightning instrumentation system.

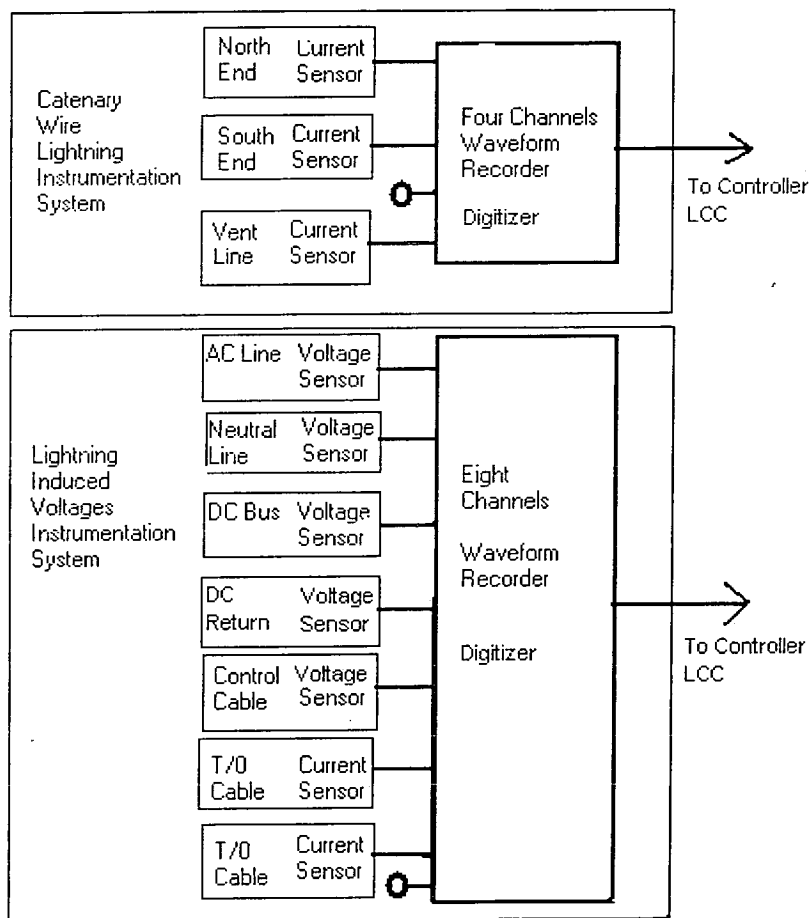
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Appendices

A. Block Diagrams (Architecture) Lightning Systems

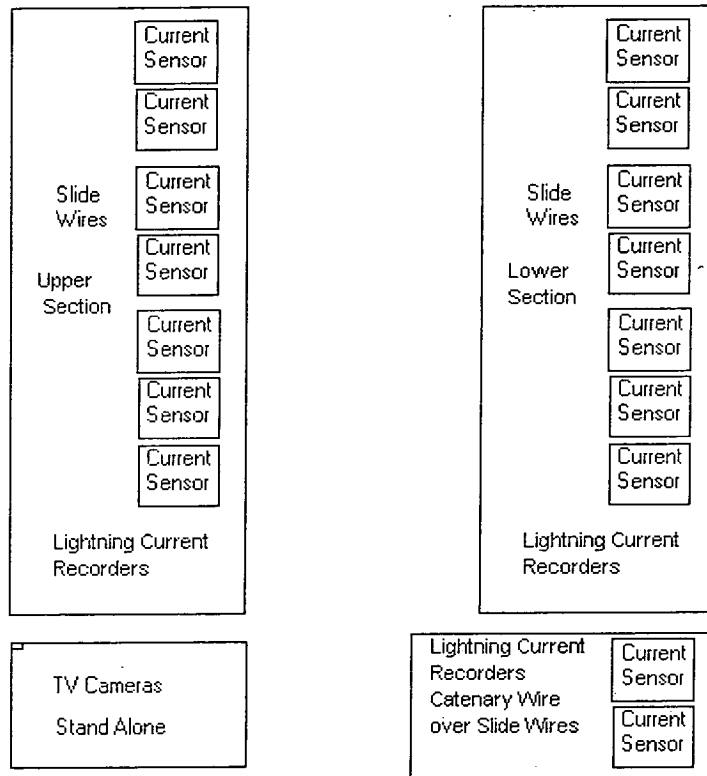
Figure 1a Actual Lightning Instrumentation Part 1



Actual Lightning Instrumentation System (Part 1 of 2)

A. Block Diagrams (Architecture) Lightning Systems

Figure 1b Actual Lightning Instrumentation Part 2

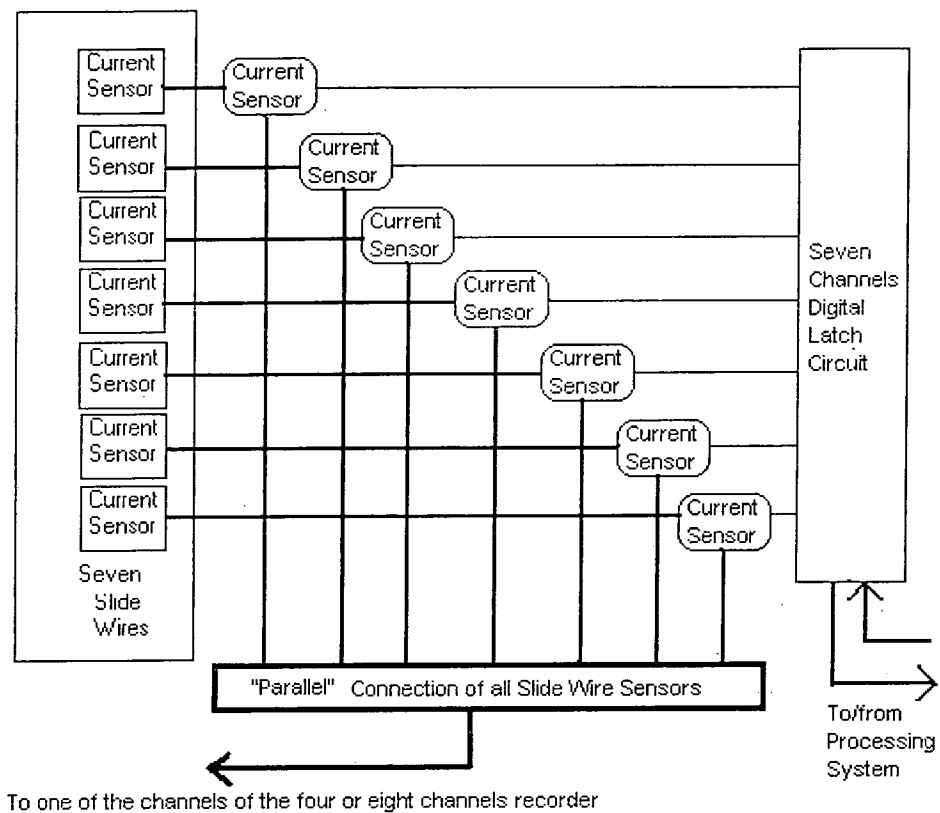


Stand Alone System

Actual Instrumentation System (Part 2 of 2)

A. Block Diagrams (Architecture) Lightning Systems

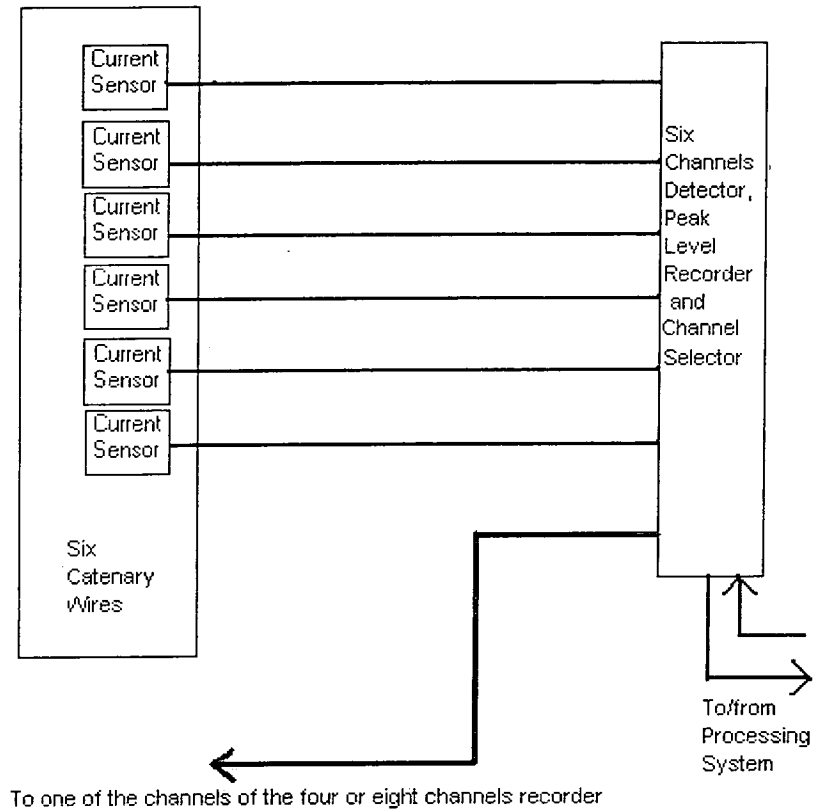
Figure 2a New Lightning Currents Recorder for Slide Wires



New Current Recorder System for Slide Wires

A. Block Diagrams (Architecture) Lightning Systems

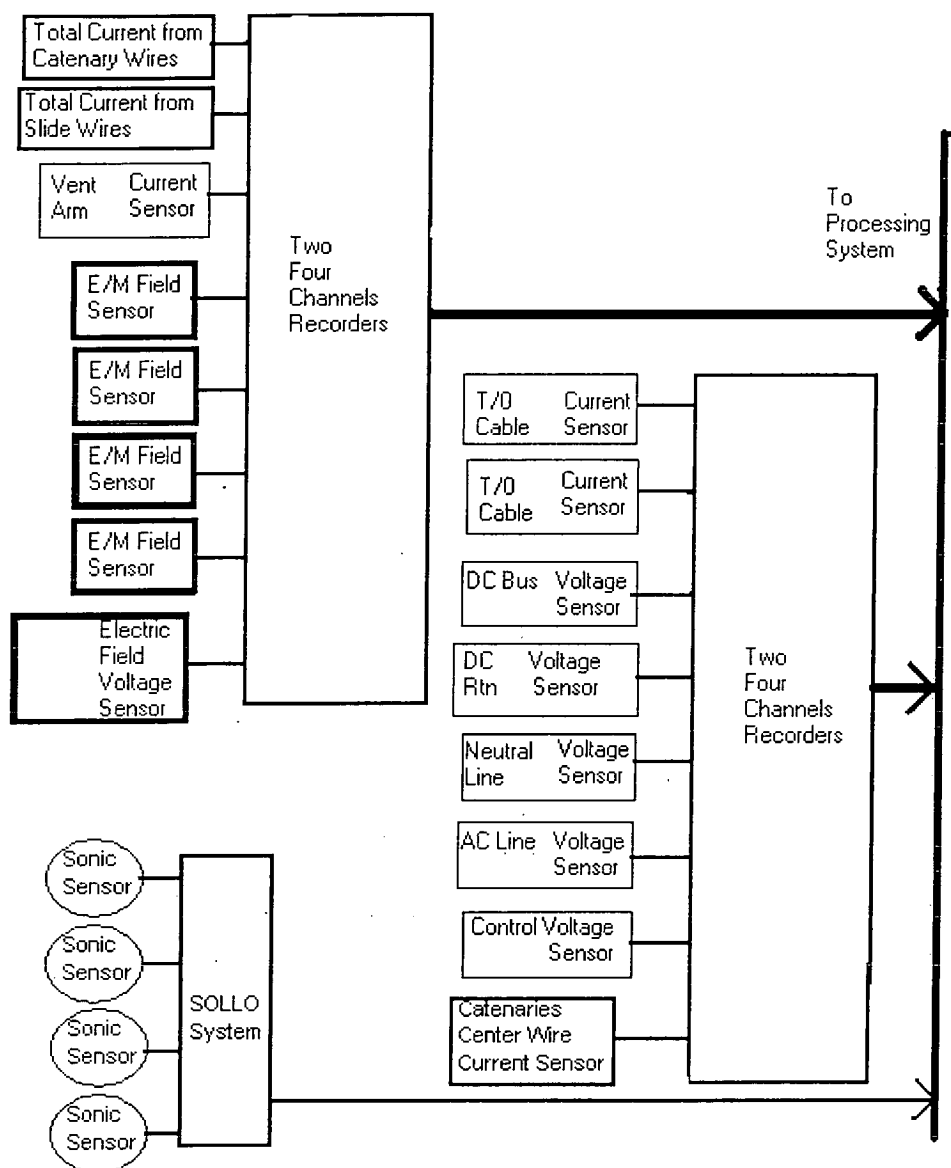
Figure 2b New Lightning Currents Recorder for Catenary Wires



New Current Recorder System for Catenary Wires

A. Block Diagrams (Architecture) Lightning Systems

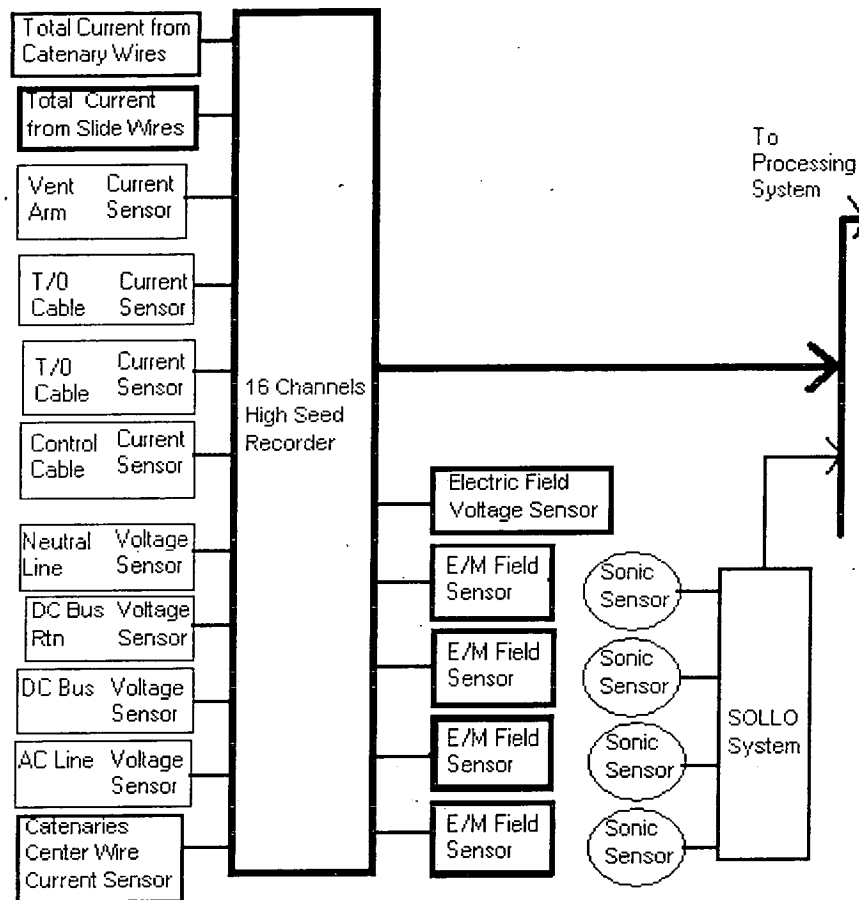
Figure 3 Modified Lightning Currents Lightning Instrumentation System (LIVIS up-grade)



Modified Lightning Instrumentation System

A. Block Diagrams (Architecture) Lightning Systems

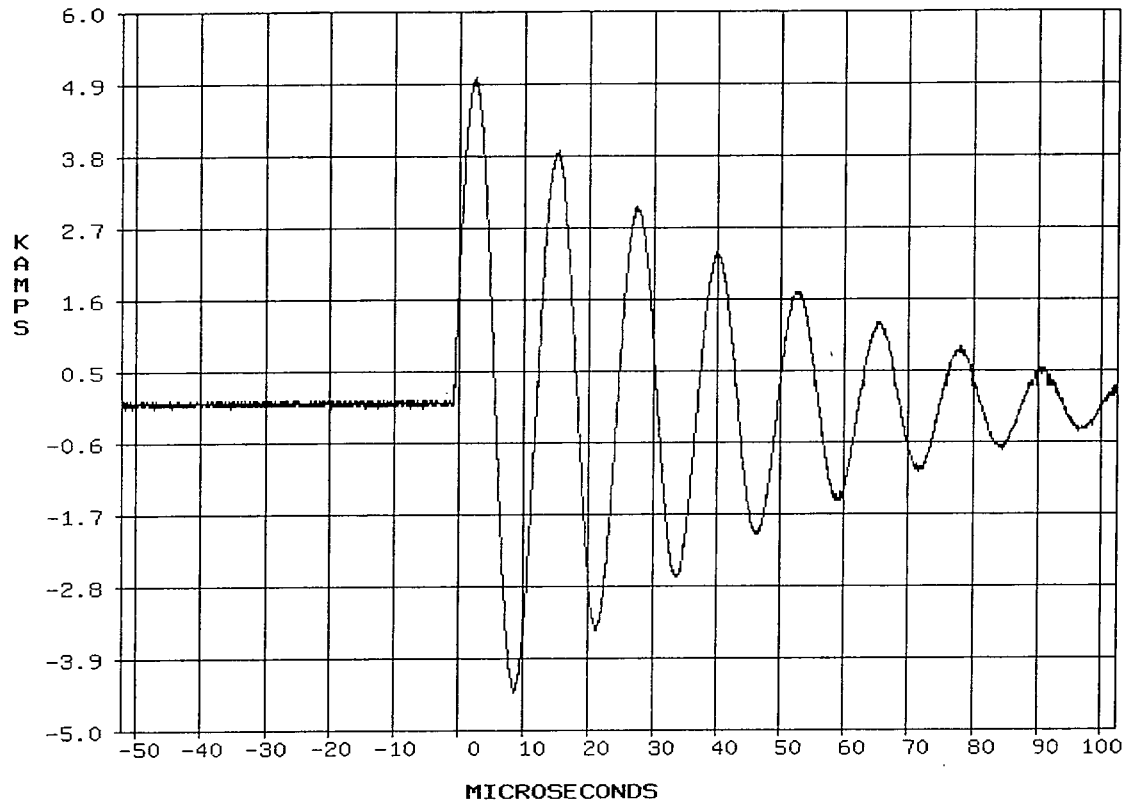
Figure 4 New Integrated Lightning Instrumentation Systems



New Integrated Instrumentation System

B. Catenary Wire Current Waveforms

Figure 5a Main Catenary Wire Current Waveform Response to Simulated Lightning Strike



B. Catenary Wire Current Waveforms

Figure 5b Main Catenary Wire Current Waveform Response to Actual Lightning Strike

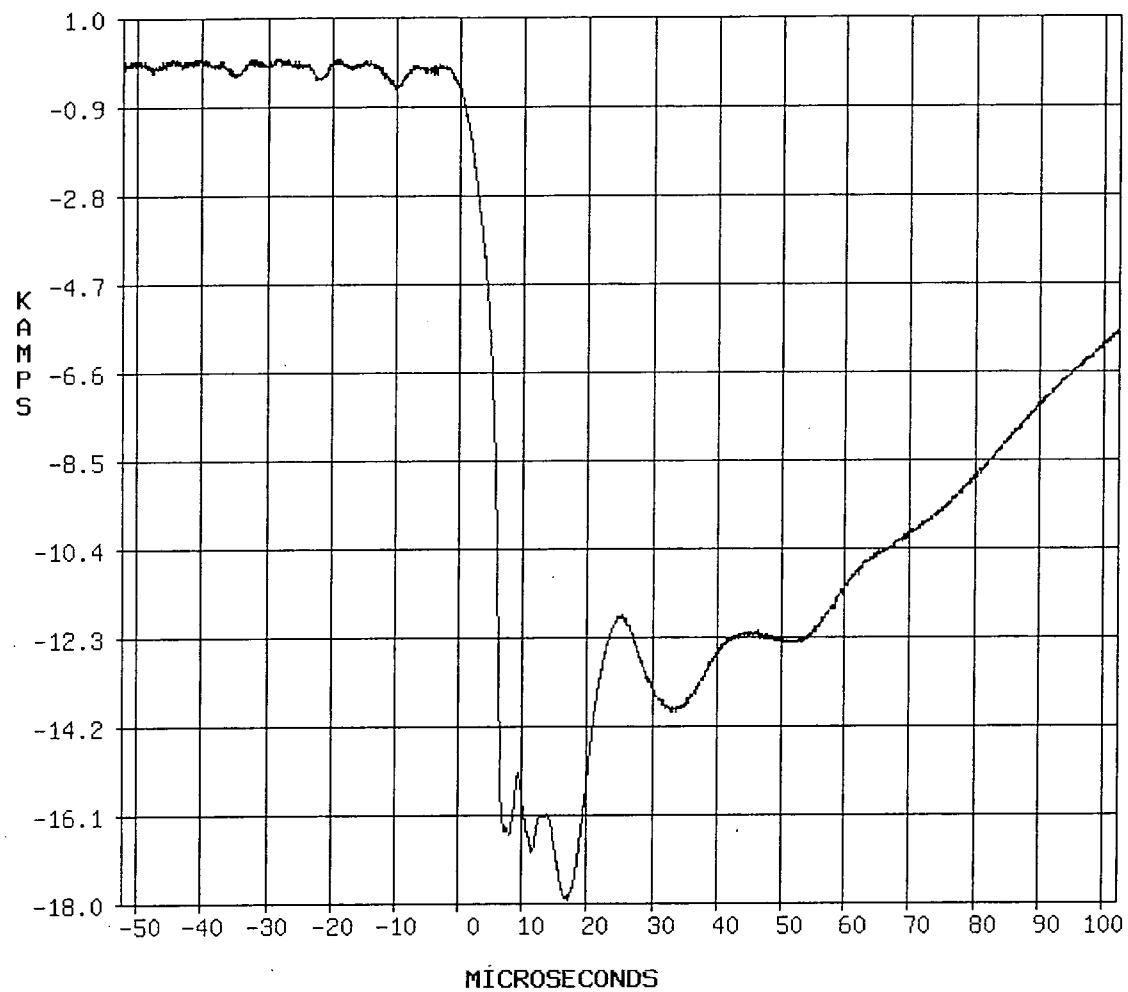
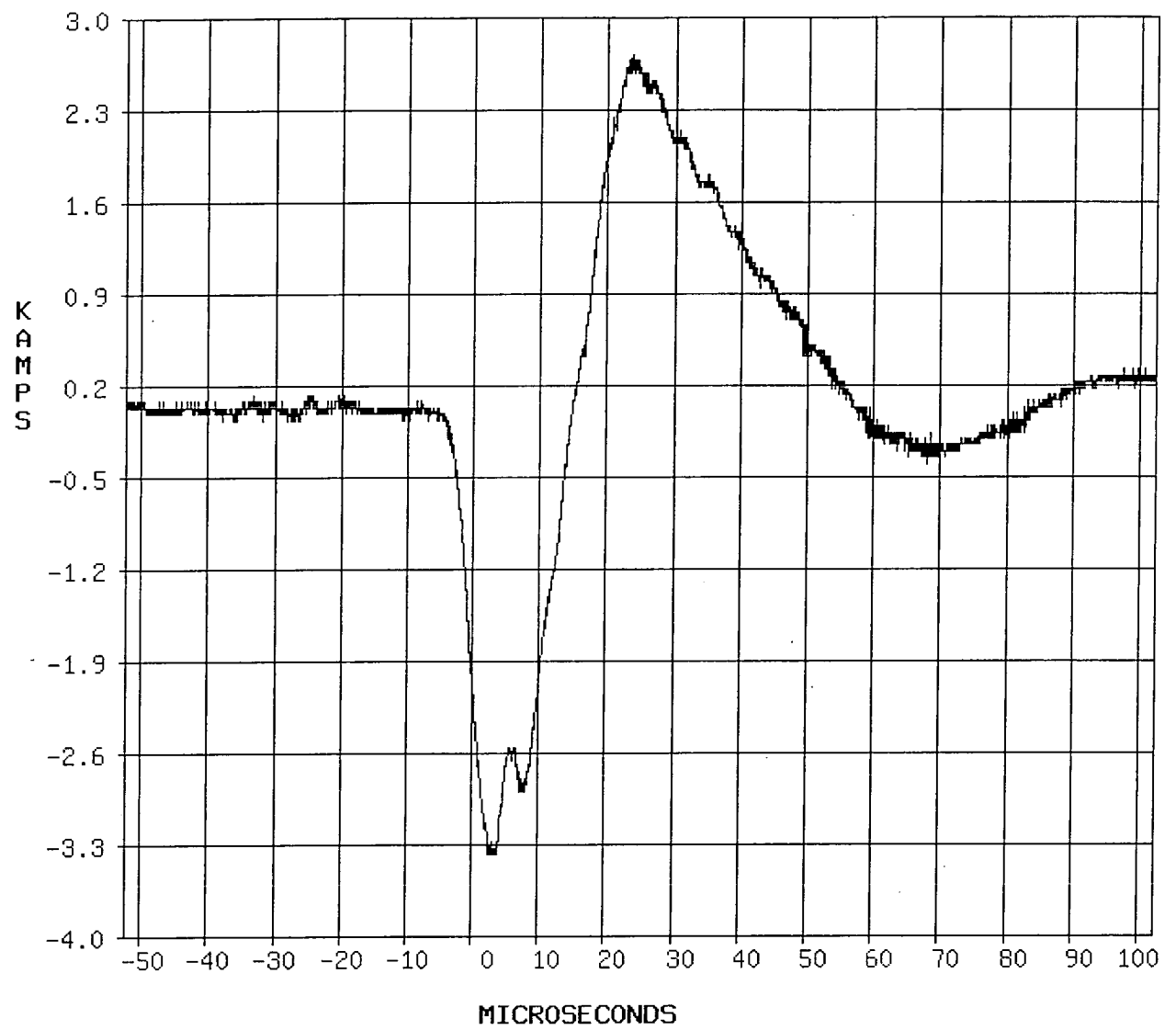


Figure 5c Main Catenary Wire Current Waveform Response to Near-by Lightning Strike
(Current Response of Catenary Wire from Induced Magnetic Field)



C. Corona Device (CD) Drawing

(Dr. Gary Godfrey is going to provide this Dreawing)

Appendix D

Pending Work

- *Determine best configuration for new catenary wires*
- *Evaluate SOLLO performance*
- *Develop new current recorder system*
- *Develop program for system integration, if LIVIS is to be up-graded*
- *Determine optimum location for new catenary wires*
- *Evaluate catenary supporting mast strength for extra wires*
- *Evaluate catenary wires for slide wires protection*
- *Investigate corona device effectiveness*
- *Evaluate catenary wires strength for extra load*
- *Determine optimum corona device dimensions, separation, quantity, and materials to use*
- *Develop a mechanism for easy installation of the corona devices*